Probing the Host Galaxy of a Luminous Quasar

Linda C. Watson[1]

ABSTRACT

We present a study of PG 1426+015, a quasar and host galaxy system at a distance of 1.3 billion light years. Quasars are intrinsically bright objects found at the center of 0.1% of local galaxies. With luminosities greater than 30 billion times that of our Sun, quasars must be powered by an exceptionally energetic phenomenon: the accretion of matter onto a black hole more than ten million times as massive as our Sun. The science goal of our study is to place PG 1426+015 on the $M_{\rm BH}$ - σ_* relation — an empirical correlation between the mass of the central black hole ($M_{\rm BH}$) and the stellar velocity dispersion of the host galaxy (σ_*). The velocity dispersion is a measure of the average random velocity of stars in a galaxy; typically more massive galaxies have larger velocity dispersions. The $M_{\rm BH}$ - σ_* relation implies that the growth of the central black hole and the stellar component of a galaxy is synchronized. This is an area of intensive research because a well-accepted theory explaining the $M_{\rm BH}$ - σ_* relation has not yet emerged. In our work, we focus on populating the high-mass end of the relation with luminous quasars because these objects are often extreme in their black hole masses and accretion rates. Previous work investigating luminous quasars on the $M_{\rm BH}$ - σ_* relation was limited by low-precision velocity dispersions. This is a symptom of the general challenge of quasar host galaxy studies: a quasar typically outshines its host galaxy by a factor of about ten. To circumvent this challenge, we obtained data using a combination of state of the art instrumentation available at the Gemini North telescope located on the summit of Mauna Kea in Hawaii: the Near-Infrared Integral Field Spectrometer (NIFS) and the recently installed Altair Laser Guide Star adaptive optics system. The technical goal of our study is to determine whether this combination of instrumentation is an aid to host galaxy studies of luminous quasars.

---

[1]Department of Astronomy, The Ohio State University. This research was completed in collaboration with my advisers Paul Martini and Bradley M. Peterson.

Using NIFS and Altair, we obtained an H-band ($1.5 - 1.8\ \mu\mathrm{m}$) spectrum of PG 1426+015 from which we measured the stellar velocity dispersion of the host galaxy to be $217 \pm 15\,\mathrm{km\,s^{-1}}$. The combination of instrumentation at Gemini North allowed us to achieve a large ratio of host to quasar light. This resulted in a velocity dispersion four times more precise than a previous measurement even though our data was obtained in a shorter net integration time. Our work demonstrates that instrumentation similar to NIFS and Altair can be used to obtain precise velocity dispersions for a larger sample of luminous quasars. Using our velocity dispersion and a previously determined black hole mass, we find that PG 1426+015 lies significantly above the M_{BH} - σ_* relation. We discuss several possible explanations for this discrepancy. With a larger sample of luminous quasars with precisely determined velocity dispersions, we can begin to consider how this observation constrains current models of the co-evolution of quasars and their host galaxies.

1. INTRODUCTION

The first quasars were discovered in the early 1960s (Edge et al. 1959; Bennett et al. 1961), followed shortly by a proposal that quasars could be powered by accretion onto black holes with masses greater than about $10^7\ M_\odot$ (Zel'dovich & Novikov 1964; Salpeter 1964), where $M_\odot$ refers to the mass of our Sun. The evidence supporting this theory has become sufficiently abundant that it is generally accepted (Peterson 1997; Ferrarese & Ford 2005). Soon after the discovery of quasars, astronomers noticed that a faint fuzz often surrounded the point-like quasar emission (Matthews & Sandage 1963). Despite this prompt discovery, it was not until the early 1980s that the fuzz was confirmed to be a galaxy, consequently proving that quasars are located in the nuclei of galaxies (Boroson et al. 1982). Verifying the connection between quasars and their host galaxies required two decades and significant technological advances because, at quasar distances, the point-like quasar outshines the comparably faint and extended host galaxy.

Recent quasar studies have focused on understanding how the accreting black hole affects its host galaxy. One of the main results from these investigations has been the discovery that black hole properties are correlated with galaxy properties (Kormendy & Richstone 1995; Ferrarese & Merritt 2000; Marconi & Hunt 2003). Arguably, the tightest of these correlations is the M_{BH} - σ_*

relation, which relates the mass of the central black hole ($M_{\rm BH}$) to the stellar velocity dispersion of the host galaxy (σ_*). The sense of the relation is such that more massive black holes reside in more massive galaxies, as traced by on-average larger random velocities. Ferrarese & Merritt (2000) initially discovered this relation in quiescent galaxies like our own galaxy, the Milky Way, which hosts an essentially dormant black hole. Subsequently Gebhardt et al. (2000) and Ferrarese et al. (2001) extended the relation to include galaxies known as Seyferts, which are the lower luminosity analogs of quasars (the division between Seyferts and quasars is at about $10^{10}\,L_\odot$, where $L_\odot$ is the luminosity of our Sun). The $M_{\rm BH}$ - σ_* relation is surprising because the stars in the galaxy are outside the gravitational sphere of influence of the black hole and therefore should know nothing of its mass. And yet the tight relation implies that black holes and their host galaxies not only know about one another — their growth is actually synchronized. Theories have been suggested to explain this correlation but none have yet shown sufficient predictive power to be well accepted.

In this study, we work towards constraining the physical mechanism that links black holes and their host galaxies by comparing the locations of active versus quiescent galaxies on the $M_{\rm BH}$ - σ_* plane. Any true offsets between these populations could signal evolution of the galaxy and/or the black hole between the actively-accreting and quiescent phase of the system. We specifically focus on measuring the stellar velocity dispersion for a high-luminosity quasar. High-luminosity quasars are particularly interesting for $M_{\rm BH}$ - σ_* relation studies because their black holes are typically the most massive and accrete at the highest rates.

However, the fact that high-luminosity quasars outshine their host galaxies presents a significant challenge for measurements of precise host galaxy velocity dispersions. The velocity dispersion is measured by calculating the width of stellar absorption features in the spectrum of a galaxy. The quasar does not exhibit these absorption features and solely adds noise to the spectrum, which dilutes the stellar features. The effect of this dilution was evident in work by Dasyra et al. (2007), which used single-slit spectra from the 8m Very Large Telescope (VLT) to measure stellar velocity dispersions for the hosts of high-luminosity quasars. This work demonstrated that CO bandhead stellar absorption features in the near-infrared could be used to constrain the stellar velocity dispersion. However, the observations were still of faint hosts with significant quasar contamination. As

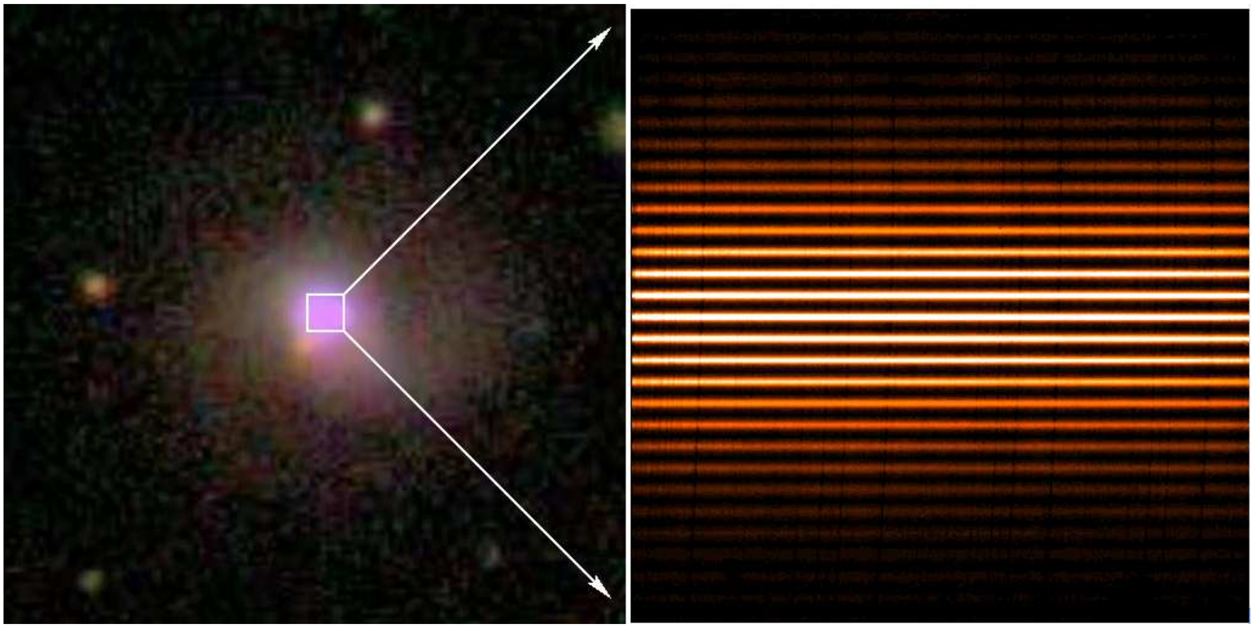

Fig. 1.— Left: image of PG 1426+015 from the Sloan Digital Sky Survey (Adelman-McCarthy et al. 2008). The white box represents the $3'' \times 3''$ FOV of NIFS, where $3''$ corresponds to a physical size of 1.6×10^4 light-years at the distance of PG 1426+015. Right: dispersed light from within the NIFS FOV. The horizontal axis is the spectral direction and the 29 spatial slices are stacked vertically.

a result, some of the host spectra were rather noisy and therefore the derived velocity dispersions had large uncertainties. We targeted the object with the most uncertain velocity dispersion in the Dasyra et al. (2007) work: PG 1426+015, which has a measured black hole mass of $1.3 \times 10^9\,M_\odot$ and a quasar luminosity of $1.3 \times 10^{12}\,L_\odot$.

To overcome the challenges of velocity dispersion measurements of the hosts of luminous quasars, we require a combination of state of the art instrumentation available at the Gemini North 8m telescope: the Near-Infrared Integral Field Spectrometer (NIFS) and the recently installed Altair Laser Guide Star (LGS) adaptive optics (AO) system. Figure 1 demonstrates the advantage of using an integral field spectrometer like NIFS. The left panel shows an image of PG 1426+015 from the Sloan Digital Sky Survey (Adelman-McCarthy et al. 2008). The white box represents the $3'' \times 3''$ field of view (FOV) of NIFS (where $1'' = 1/206265$ radians). NIFS spatially divides the FOV into 29 slices and disperses each of these components. The right panel shows an image of the dispersed light. The spectral direction extends horizontally and the 29 spatial slices are stacked vertically. The majority of spectrographs (including the instrument used in Dasyra et al. 2007) use only a single slit, which disperses an area approximately equivalent to a single slice in NIFS. As a result, using an integral field spectrometer should allow us to gather substantially more host galaxy light than is possible with a normal single-slit spectrograph. LGS AO is a further aid to velocity dispersion studies because it allows us to minimize the quasar contribution to the spectrum. To use LGS AO, one points a laser in the direction of the astronomical object. The laser interacts with atoms in the atmosphere, which emit photons in response. One monitors the changes in the shape of this "laser star" that are due to changes in the atmosphere. The shape of the telescope mirror can then be manipulated to correct for these atmospheric aberrations. This technique can dramatically increase the image quality. In the case of velocity dispersion studies, LGS AO can be used to confine the quasar light to the central few pixels of the image. We can then remove this quasar contribution from the spectrum without excluding a significant amount of host galaxy light. In short, we expect that NIFS will help us maximize the galaxy contribution to our spectrum while the Altair LGS AO system will help us minimize the quasar contribution to the spectrum. The technical goal of this work is to determine whether this combination of instrumentation results in a more precise stellar velocity dispersion.

2. OBSERVATIONS AND DATA ANALYSIS

The observations of PG 1426+015 and the stellar template HIP 75799 were carried out at the 8m Gemini North telescope, which is located on the summit of Mauna Kea in Hawaii, on 2007 February 6-7, and April 29 using NIFS (McGregor et al. 2002). Three additional stellar templates — HD 84769, V* VU CVn, and BD+23 1138 — were observed on 2008 February 12, 14, and 15. NIFS was fed by Altair, the AO system at Gemini North (Herriot et al. 2000; Boccas et al. 2006). Our observations were obtained in the H-band ($1.5 - 1.8\ \mu$m), which contains many strong atomic and molecular stellar absorption features, including Mg I 1.488μm, Mg I 1.503μm, CO(3-0) 1.558μm, CO(4-1) 1.578μm, Si I 1.589μm, and CO(6-3) 1.619μm.

Our host galaxy spectrum is the difference between a $1''$ and $0.1''$ radius extraction, where $1''$

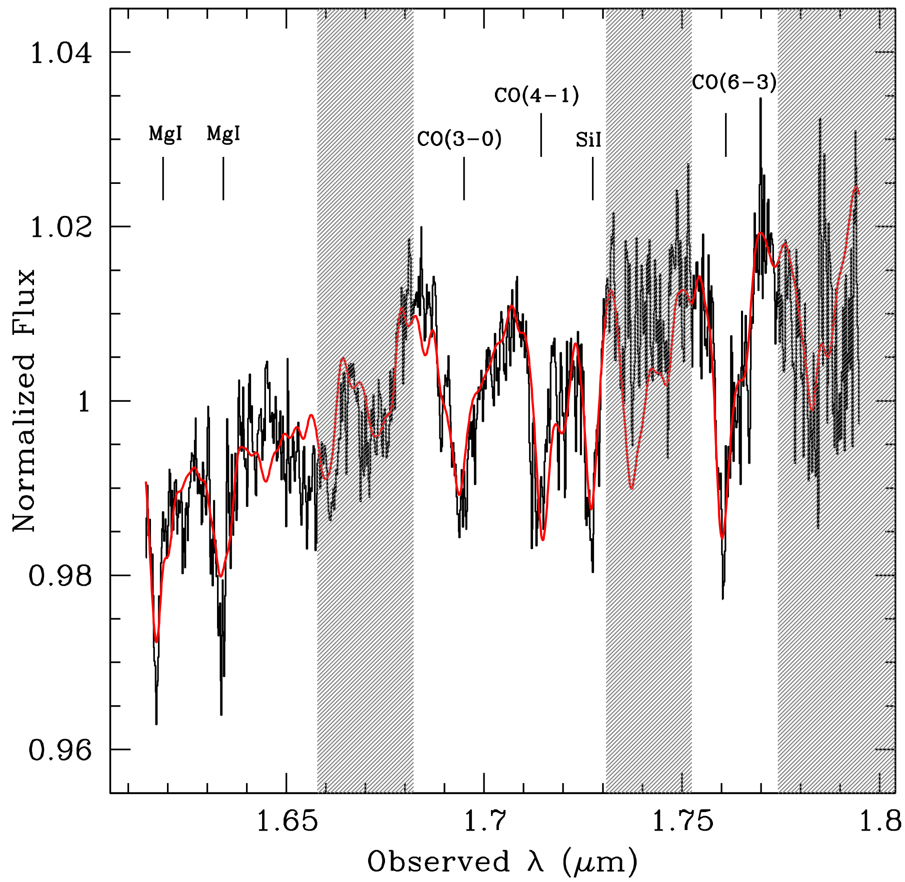

Fig. 2.— Observed-frame host galaxy spectrum of PG 1426+015, normalized by the mean flux. The red curve shows the spectrum of our best-fit stellar template, broadened to fit the width of the host galaxy absorption features. The gray bands show regions excluded from our fit.

corresponds to a physical size of 5.2×10^3 light-years at the distance of PG 1426+015. We empirically chose these values to include as much host galaxy light as possible while also minimizing the quasar contribution. The LGS system allowed our inner radius to be substantially smaller than would have been possible under natural atmospheric conditions.

We measured the stellar velocity dispersion using the penalized pixel fitting (pPXF) method of Cappellari & Emsellem (2004). This method assumes that the host galaxy spectrum is represented by a convolution of a stellar template spectrum and the line-of-sight velocity distribution (LOSVD), which describes the random velocities of the stars in the galaxy.

3. RESULTS AND DISCUSSION

Figure 2 shows the observed-frame host galaxy spectrum of PG 1426+015 obtained with NIFS and Altair. The stellar absorption features we used to determine the velocity dispersion are marked while the shaded regions designate spectral regions excluded from our pPXF fit because they were affected by atmospheric emission and absorption. The smooth red curve shows the spectrum of the stellar template that best represents the population of stars in the galaxy. We have broadened the absorption features by the best-fit galaxy LOSVD. Using a variety of template fits, we determine that the stellar velocity dispersion for the host galaxy is $217 \pm 15\,\mathrm{km\,s^{-1}}$. Our uncertainty takes into account both the error in individual template fits and the error due to the fact that a single star cannot represent the composite spectrum of a galaxy.

The signal-to-noise (SNR) ratio of the NIFS spectrum is larger than the SNR of the single-slit VLT spectrum from Dasyra et al. (2007) even though the NIFS spectrum was obtained in less than half the time. In addition, the velocity dispersion we derived is four times more precise than the value determined from the VLT spectrum. The high SNR and precise velocity dispersion are evidence of the combined advantages of NIFS and the Altair LGS AO system for host galaxy velocity dispersion studies of luminous quasars.

In Figure 3, we use our measurement of the stellar velocity dispersion and the black hole mass determined in Peterson et al. (2004) to place PG 1426+015 on the $M_{\rm BH}$ - σ_* relation. All the points in the figure represent galaxies with actively-accreting black holes: the blue squares represent Seyfert galaxies from Onken et al. (2004), the red squares represent quasars studied in the Dasyra et al. (2007) work using single-slit VLT spectra, and the star represents the position of PG 1426+015 using our new velocity dispersion value. For comparison, the red square to the immediate left of the star indicates the position of PG 1426+015 in the Dasyra et al. (2007) work. The solid line denotes a fit to the local quiescent galaxy $M_{\rm BH}$ - σ_* relation from Tremaine et al. (2002).

Although PG 1426+015 is now closer to the quiescent galaxy $M_{\rm BH}$ - σ_* relation, it is also now more significantly discrepant with the relation because our measurement has a smaller error bar. From the few active galaxy data points that we have at the high-mass end of the relation, there

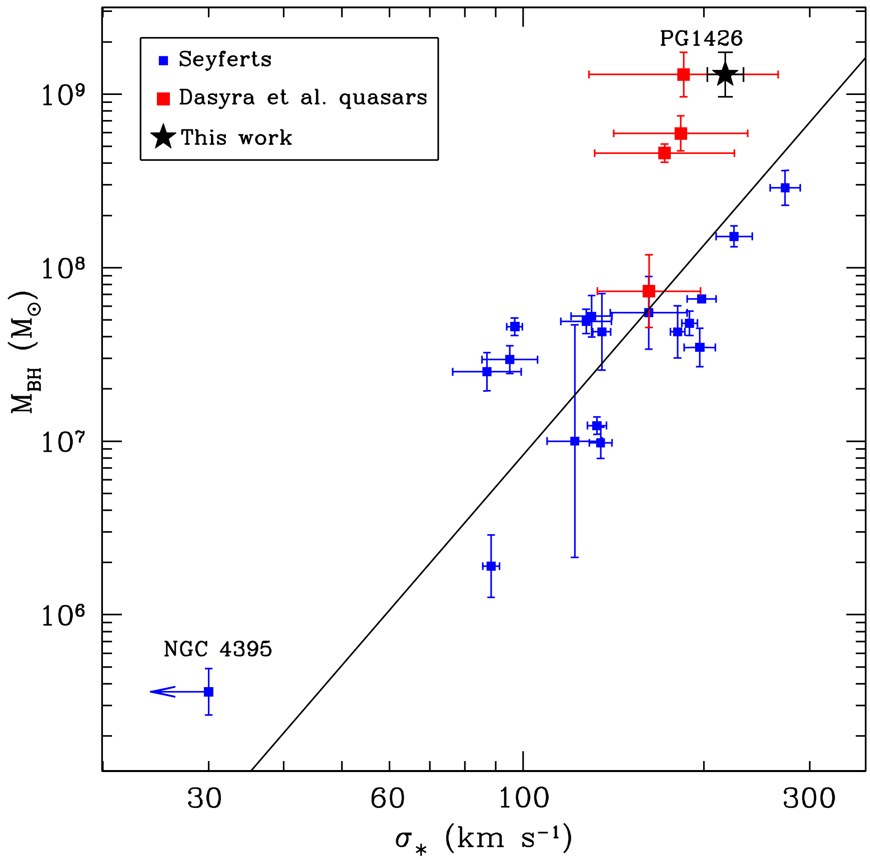

Fig. 3.— The $M_{\rm BH}$ - σ_* relationship for quasars and Seyferts. Blue squares represent Seyfert galaxies, red squares represent quasars studied by Dasyra et al. (2007) using single-slit VLT data, and the star represents the position of PG 1426+015 using the velocity dispersion derived in this work. The black line represents the Tremaine et al. (2002) fit to the quiescent galaxy $M_{\rm BH}$ - σ_* relation.

is a suggestion that these objects lie above the trend. It is certainly possible that more data will show that we have simply been victims of small number statistics. Alternatively, underestimated velocity dispersions or selection biases could spuriously drive quasars above the quiescent galaxy $M_{\rm BH}$ - σ_* relation (Dasyra et al. 2007; Lauer et al. 2007). Finally, and most importantly, the black hole masses of high-luminosity quasars may be overestimated. All the points in Figure 3 have black hole masses estimated by reverberation mapping. This technique provides the radius of the broad-line region (BLR), which is a region of rapidly moving gas that is typically at a distance of tens to hundreds of light-days from the black hole. Assuming the gravity of the black hole is the dominant force acting on the BLR gas, one can combine this radius with a measure of the BLR gas velocity and arrive at an estimate for the black hole mass. But this mass is uncertain due to the unknown geometry of the BLR. We currently simply include a constant scale factor in mass calculations that on average accounts for the geometry. Onken et al. (2004) calculated this scale factor for the lower-luminosity Seyfert population, but it could vary with luminosity. If the true quasar scale factor is smaller than the Seyfert scale factor, quasars would falsely appear above the relation in Figure 3. The degeneracy between true offsets from the quiescent galaxy $M_{\rm BH}$ - σ_* relation and scale factor differences between populations complicates the interpretation of our results.

Determining if one of the above possibilities is correct could broaden our understanding of galaxy formation, black hole growth, and BLR geometry. But if we can rule out each of the above possibilities and high-mass quasars do in fact lie above the quiescent galaxy $M_{\rm BH}$ - σ_* relation, the direction and magnitude of the offset should constrain current models of the co-evolution of black holes and their host galaxies. This measurement would significantly impact the field. To accomplish these goals, we will require a larger sample of high-mass quasars with measured black hole masses and precise stellar velocity dispersions. We are in the process of obtaining this larger sample and are currently analyzing spectra to derive velocity dispersions for two additional quasars that were observed in fall 2008.

4. CONCLUSIONS

We obtained H-band observations of PG 1426+015 using NIFS and the Altair LGS AO system on the Gemini North telescope. This combination of instrumentation provides a unique tool for studying the hosts of luminous quasars. This is demonstrated by the high SNR spectrum of the quasar host galaxy presented in this work as well as our precise measurement of the stellar velocity dispersion.

Our measured velocity dispersion and the Peterson et al. (2004) black hole mass place this quasar significantly above the $M_{\rm BH}$ - σ_* relation for local, quiescent galaxies. We have explored a number of reasons why PG 1426+015 might lie above the $M_{\rm BH}$ - σ_* relation. We can determine which of these is correct by measuring precise velocity dispersions for more high-luminosity quasars with accurate black hole masses. With this expanded dataset, we may be able to constrain models for the synchronized evolution of black holes and their host galaxies.

REFERENCES

Adelman-McCarthy, J. K., et al. 2008, ApJS, 175, 297

Bennett, A. S., 1961, MmRAS, 68, 163

Boccas, M., et al. 2006, SPIE, 6272, 114

Boroson, T. A., Oke, J. B., & Green, R. F. 1982, ApJ, 263, 32

Cappellari, M. & Emsellem, E. 2004, PASP, 116, 138

Dasyra, K. M., et al. 2007, ApJ, 657, 102

Edge, D. O., Shakeshaft, J. R., McAdam, W. B., Baldwin, J. E., & Archer, S. 1959, MmRAS, 68, 37

Ferrarese, L., & Ford, H. 2005, Space Sci. Rev., 116, 523

Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9

Ferrarese, L., Pogge, R. W., Peterson, B. M., Merritt, D., Wandel, A., & Joseph, C. L. 2001, ApJ, 555, L79

Gebhardt, K., et al. 2000x, ApJ, 543, L5

Ghez, A. M., Salim, S., Hornstein, S. D., Tanner, A., Lu, J. R., Morris, M., Becklin, E. E., & Duchêne, G. 2005, ApJ, 620, 744

Herriot, G., et al. 2000, SPIE, 4007, 115

Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581

Lauer, T. R., Tremaine, S., Richstone, D., & Faber, S. M. 2007, ApJ, 670, 249

Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21

Matthews, T. A., & Sandage, A. R. 1963, ApJ, 138, 30

McGregor, P., et al. 2002, SPIE, 4841, 178

Onken, C. A., Ferrarese, L., Merritt, D., Peterson, B. M., Pogge, R. W., Vestergaard, M., & Wandel, A. 2004, ApJ, 615, 645

Peterson, B. M. *An Introduction to Active Galactic Nuclei*. Cambridge: Cambridge University Press, 1997

Peterson, B. M., et al. 2004, ApJ, 613, 682

Salpeter, E. E. 1964, ApJ, 140, 796

Smith, H. J., & Hoffleit, D. 1963, AJ, 68, 292

Tremaine, S., et al. 2002, ApJ, 574, 740

Zel'dovich, Ya. B., & Novikov, I. D. 1964, Sov. Phys. Dokl., 158, 811

This preprint was prepared with the AAS LaTeX macros v5.2.